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SDN-Enabled Li-Fi/Wi-Fi Wireless Medium Access Technologies Integration Framework

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***Abstract*—The integration of Li-Fi and IEEE 802.11x Wi-Fi wireless access networks represents an opportunity for users to receive secure ubiquitous indoor HD video and voice services, and internet service providers to diversify services portfolio. For the first time, this paper introduces an application-medium access control (MAC) cross-layer scheme for integrating Li-Fi and Wi-Fi access networks using software-defined networking. The scheme comprises a flow admission control mechanism, which inter-operates with a mechanism that dynamically allocates resources of Li-Fi and Wi-Fi MAC layers. It leverages the capacity diversity of Li-Fi and Wi-Fi access networks to support OoS per-flow service class. The proposed scheme runs in the SDN controller and interacts with SDN agents functionalities running in the APs, which consider traffic parameters of applications running on mobile devices to efficiently support real-time services. The parameters underlying Li-Fi and Wi-Fi AP MAC protocols can be configured by the proposed SDN scheme to support dynamic and granular services provisioning to end-users.**

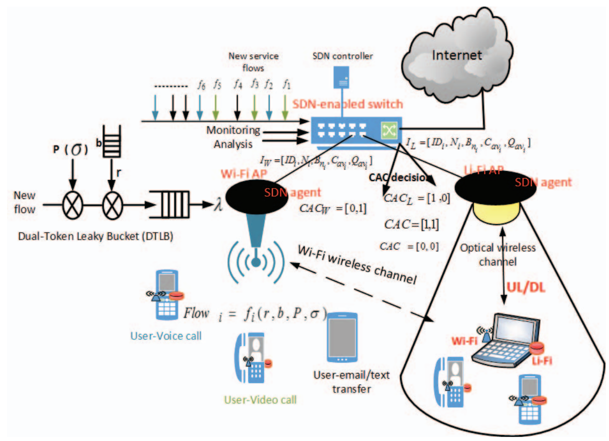

Fig. 1. A SDN-enabled Li-Fi/Wi-Fi access network.

I. Introduction

Indoor wireless communications are often established to run real-time applications (e.g. VoIP, IP Video streaming, HDTV, teleconference calls), which require rigorous quality-of-service (QoS) to enable users to experience seamless and transparent services. The new demand for wireless spectrum and ubiquitous wireless communication accelerates the efforts of mobile industry to enable Li-Fi optical wireless technology in wireless devices to support data rate at optical speed [1], [2]. Wireless technologies enabled in mobile devices (MDs) should be integrated to support an intelligent inter-operation among its underlying wireless access networks to improve quality-of-experience (QoE) of users [3] and enable wireless and mobile operators to diversify their communication services portfolio [4], [5].

Software defined networking (SDN) provides a practical approach to enable coexistence of mobile wireless technologies [6], [7], [8], [4]. SDN is deployed to leverage the diversity of IEEE 802.11e Wi-Fi standard and Li-Fi optical WLAN to support ubiquitous indoor real-time applications, as shown in Fig. 1. The carrier sense multiple access with collision avoidance (CSMA/CA) protocol supports multiple user access in Wi-Fi; And the orthogonal frequency-division multiple access (OFDMA) protocol supports multiple user access in Li-Fi access network. To account for packets collision in IEEE 802.11e Wi-Fi access network and signal obstructions in Li-Fi access network, each admitted real-time flow is assigned an extra time to access the medium or bit-rate to transmit, respectively. This includes the transmission time, the surplus medium access allowance (SMAA), overhead, for compensating packet errors, collisions and interference.

Traffic flows generated from applications running on MDs pass through a Dual-Token Leaky Bucket (DTLB), which characterizes it with specific traffic characteristics (TSPEC), namely mean data leaking rate (r), peak data rate (P), bucket size (b), burst size (maximum packet size) (σ) [9]. Thus, the QoS requirements of traffic flow-i, $f_i(r, b, P, \sigma)$, are defined in terms of the DTLB characteristics which are enforced at APs. As illustrated in Fig. 1, the SDN controller coordinates the admission of traffic flows with the software agents running in the access points (APs) and the MDs collecting the global view of these access networks. The global view includes the f_i identifier (ID_i), number of f_i(N_i), bandwidth requirement of f_i (B_{n_i}), available bandwidth and buffer for f_i (C_{av_i}, Q_{av_i}), and collision traffic data rate of MDs. This information is analyzed by the SDN controller to perform f_i admission control (FAC) in Li-Fi, $\mathrm{CAC}_L = [1, 0]$, Wi-Fi, $\mathrm{CAC}_W = [0, 1]$, in both APs by splitting traffic load between Li-Fi and Wi-Fi APs, CAC $= [1, 1]$, or reject the f_i, CAC $= [0, 0]$.

A SDN scheme is developed to enable inter-operating medium access controllers of Li-Fi and Wi-Fi wireless tech-

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nologies to support multiple services, particularly admitting more real-time services while maintaining an acceptable level of capacity sharing with other service classes. It leverages the diversity of the integrated Li-Fi/Wi-Fi wireless technologies to dynamically support services that can adapt to the requirements of users. The developed scheme combines the operations of the contention-based CSMA/CA channel access mechanism, referred to as Enhanced Distributed Channel Access (EDCA), which enables users access in Wi-Fi access network, and our proposed polling-based channel access mechanism in Li-Fi access network, referred to as polling-based flexible soft slot reservation protocol (P-FSRP).

The rest of this paper is structured as follows. In Section II the per-flow QoS requirements are expressed in terms of throughput and buffer space at AP. In Section III the differentiated medium access (DMA) support is explained in Li-Fi and IEEE 802.11e Wi-Fi. In Section IV the differentiated medium access control scheme that controls differentiated medium resources in the integrated Li-Fi and Wi-Fi access network is explained. In Section V the results are discussed and comments made on its trends. In Section VI the conclusions and findings are highlighted.

II. Per-Flow Resource and QoS Requirements

The software drivers of IEEE 802.11e and Li-Fi wireless technologies installed in a MD define the Traffic SPECification (TSPEC) of each traffic flow class supported in these wireless standards. The MD uses the TSPEC of flows to signal its QoS requirements to the AP, as shown in Fig. 1. The amount of traffic generated from flows passing through the DTLB filter during the time period $(s, t+s]$ is characterized by an arrival curve expressed as: $A(s, t+s) = Min(Pt, rt+b)$, where the bucket size of the DTLB filter is determined as: $b = \sigma(1 - r/P)$ [10]. The DTLB polices and enforces the TSPEC parameters of admitted flows through conforming packets to their TSPEC. These parameters are used to derive the per-flow QoS requirements.

A. Per-flow statistical guaranteed service rate

For constant bit-rate (CBR) voice traffic flows, some extra bit-rate should be allocated in addition to its required guaranteed bit-rate (GBR) to account for any failed or lost packets on the Li-Fi or Wi-Fi wireless access medium. The delivery bit-rate (DBR_i) of f_i is calculated as follows:

$$DBR_i = \frac{GBR_i}{1 - P_{err_i}}; \tag{1}$$

where P_{err_i} denotes the probability of error in transmitting packets of f_i.

The VBR video traffic is bursty and thus it is rigorously policed through the DLTB. A VBR flow is assigned a GBR less than its peak data rate, but enough to satisfy its delay and throughput requirements. A VBR f_i is assigned a GBR$_i$ as a function of its delay requirement, d_i [9]:

$$GBR_i = \frac{\sigma_i}{d_i + \frac{\sigma_i}{P_i}}. \tag{2}$$

Based on (1) and (2), the statistical GBR (DBR) can be expressed mathematically as:

$$DBR_i = \frac{\sigma_i}{(d_i + \frac{\sigma_i}{P_i})(1 - P_{err_i})}. \tag{3}$$

When P_{err_i} is small, more real-time flows can be admitted as less extra bit-rate allowance is allocated to traffic flows and vice-versa. In Wi-Fi, the GBR$_i$ is achieved by allocating a duration of time to f_i to access Wi-Fi medium. In Li-Fi, the GBR$_i$ is achieved by allocating a number of time slots to f_i to access the Li-Fi medium. The Li-Fi spectrum is formed of a number of sub-channels comprising each a number of subcarriers. Denoting the achievable data rate of MD-i assigned the subchannel-j in a frame t by DBR$_{ij}(t)$. In each frame, the MD-i is serviced, if its channel data rate is greater than its minimum physical data rate threshold, R_{th_i}, expressed as:

$$DBR_{ij}(t) \geq R_{th_i} \;\; \forall j \in J. \tag{4}$$

The time slots are allocated to f_i until its maximum limitation of α slots, as follows:

$$DBR_i = \frac{\alpha_i \cdot t_{slot} \cdot R_{th_i}}{T_f}; \tag{5}$$

where t_{slot} is the time slot duration; T_f is the frame duration, as shown in Fig. 2a. This ensures the throughput of active flows while controlling Li-Fi medium access fairness among supported traffic classes. The smaller the value of α the more traffic flows can share the spectrum. The physical channel rate of MD-i, R_{th_i}, may dictate the value of α to support provisioning of services differentiation while maintaining an acceptable fairness level among active MDs. For MD-i to receive a DBR$_i$ while using a modulation and coding scheme value MCS$_i$, it would require a number of slots, given by $\alpha_i = \frac{DBR_i \times T_f}{MCS_i}$. The value of MCS determines the number of bits transmitted per subcarrier.

B. Per-flow buffering space

CBR and VBR flows require a very small packet drop rate. The CBR flows are assigned GBR based on (1), which avoids CBR packets queuing. The packet drop rate of the VBR flow depends on the DTLB parameters. To achieve a small packet drop rate for VBR flow packets, the size of its designated queue, Q$_{VBR}$, in the MD and the AP should satisfy the following constraint [11]:

$$Q_{VBR} \geq \frac{d \times \sigma(P - r)}{d(P - r) + \sigma(1 - \frac{r}{P})}. \tag{6}$$

A new flow, f_{K+1}, requests a GBR is admitted by the data rate-based FAC mechanism subject to the following constraint:

$$DBR_{K+1} + \sum_{k=1}^{K} DBR_k \leq C_{LiFi||WiFi}(t); \tag{7}$$

where $C(t)$ is the available capacity on the Li-Fi or the Wi-Fi channel at the time t.

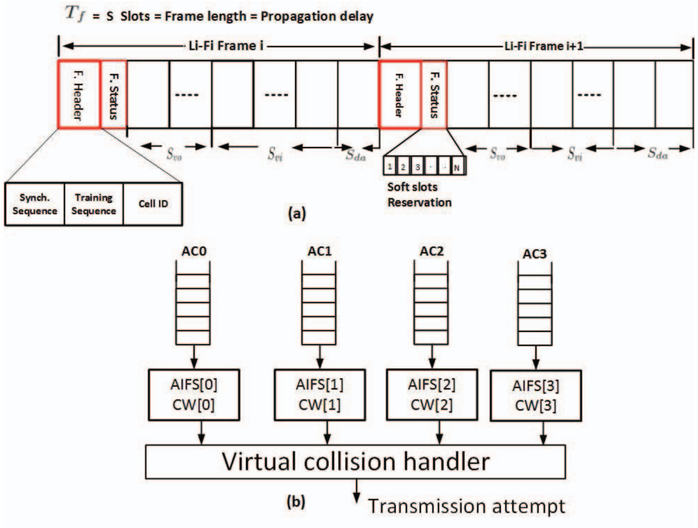

Fig. 2. (a) A multiuser frame format in Li-Fi access networks, (b) Virtual queues in IEEE 802.11e EDCA.

III. Li-Fi and Wi-Fi Differentiated Medium Access

The application layer generates traffic packets tagged with labels indicating its priority service class. The different classes gain differentiated access to the Li-Fi and Wi-Fi medium to guarantee the per-flow QoS requirement. To support differentiated Li-Fi medium access, a novel Li-Fi frame structure and P-FSRP to transport a dynamic number of CBR, VBR and best effort (BE) traffic flows are introduced, as shown in Fig. 2a. The number of slots allocated to each service class is controlled based on the value of α set in (5) for each supported traffic class in Li-Fi access network. The P-FSRP supports different Li-Fi medium access types (MATs), which are differentiated in terms of the number of slots allocated to each service class in each frame. A traffic flow is assigned a MAT that guarantees its minimum transmission rate while guaranteeing fairness among the MDs that generate the different types of flow based on adjusting the value of α.

In a frame-i, the MDs report its traffic flows to its AP and make a soft slot reservation. The AP computes the slots grant table which determines the number of slots to be allocated to active traffic classes in the next frame-$i+1$. The packets which cannot be served in the frame-$i+1$ are either transported in the next frame-$i+2$ or diverted to the Wi-Fi access network. The number of slots allocated to CBR voice, VBR video, BE flows vary from frame to frame based on the status of the MDs in terms of requested data rate and flows packets arrived (queue length). The $\alpha's$ thresholds which determine the number of slots to be assigned for each service class is dynamically changed by the SDN controller based on network status in terms of real-time traffic load and available capacity of APs. This enables bandwidth aggregation of both APs and the dynamic allocation of OFDM resources to support variable number of services with granular resource allocation.

The IEEE 802.11e Wi-Fi network supports various priority service classes based on a hybrid coordination function (HCF) integrated in the CSMA/CA protocol managing the IEEE 802.11x Wi-Fi MAC. The HCF function supports two different MAC mechanisms: i) centrally controlled channel, termed HCF controlled channel access (HCCA); and ii) contention-based channel access, termed EDCA [9], [12]. The HCCA mechanism provides a parameterized QoS service which enables a MD to negotiate the QoS requirements of generated traffic flows with the HCF. It provides QoS priority differentiation via a random distributed mechanism. The EDCA mechanism sets the parameters characterising CSMA/CA protocol to different values, and each corresponds to a different MAT, as shown in Fig. 2b.

The supported MATs are differentiated based on varying the period of time during which a MD senses the medium access availability, arbitration inter-frame space (AIFS), and the length of the contention time window, CW_{mn}. The EDCA mechanism supports four different MATs, thus for the MAT$_i$, $i \in (0, ..., 3)$, $CW_{min}[i] \geq CW_{min}[j]$, $CW_{max}[i] \geq CW_{max}[j]$, and $AIFS[i] > AIFS[j]$. To grant the MAT$_i$ to a flow-i, the EDCA uses $AIFS[i]$, $CW_{min}[i]$, $CW_{max}[i]$, instead of the default values of the CSMA/CA parameters, DIFS (data inter-frame space), CW_{min} and CW_{max}, respectively. A MAT with smaller values of these parameters shorten the waiting time to access the Wi-Fi wireless channel. The admitted traffic flows in each MAT are given a transmission opportunity (TXOP) to access the medium to retransmit lost packets. The values of the different CSMA/CA parameters that support the different MATs and the assigned TXOPs to the different traffic flows are periodically announced to MDs by the AP via periodically transmitted beacon frames. The Wi-Fi AP updates these values based on the channel conditions and the network traffic load. The SDN controller may influence this update to redirect traffic flows with various data rates to Li-Fi and vice-versa.

IV. Differentiated Medium Access Control

For MDs that generate CBR or VBR traffic flows, the FAC mechanism considers the SMAA. For the IEEE 802.11e Wi-Fi AP, the FAC mechanism admits a new traffic flow that requires $TXOP_i$, if simultaneously can support the QoS of the already admitted real-tim flows. An AP grants a MD a duration of time to send generated flow packets within its delay bound. A MD that transmits at data rate (R_i) is assigned a TXOP$_i$ [9]:

$$N_{p_i} = \lceil \frac{SMAA \cdot GBR_i}{L_p} \rceil \tag{8}$$

$$T_{p_i} = \frac{L_p}{R_i} \tag{9}$$

$$TXOP_i = max\lceil \frac{N_{p_i} \cdot L_p}{R_i}, \frac{L_{p_{max}}}{R_i} + OH \rceil; \tag{10}$$

where T_{p_i} is the packet(p) transmission time of f_i; $L_{p_{max}}$ is the maximum packet size (length) of f_i; N_{p_i} is the number of packets of f_i; OH is the overhead.

The APs may know the collided packets or those encountered errors, but it may not know which MD generated them. A MD$-i$ knows the number of transmitted packets of each flow

$-j$, $m^j_{i_{tx}}$, and those received by the higher application layer, $m^j_{i_{rx}}$. The lost flows or encountered errors packets, which represent the difference between the sent and received packets, are transmitted again using the SMAA calculated by Li-Fi and Wi-Fi APs as follows:

$$SMAA^j_{i_{LiFi}}(n) = \frac{(m^j_{i_{tx}}(n-1) - m^j_{i_{rx}}(n-1))L_p}{T_p} \quad (11)$$

$$SMAA^j_{i_{WiFi}}(n) = \frac{(m^j_{i_{tx}}(n-1) - m^j_{i_{rx}}(n-1))L_p}{R_i}; \quad (12)$$

where $m^j_{i,tx}(n-1)$ and $m^j_{i,tr}(n-1)$ are the number of packets transmitted by the MD-i and received from the corresponding application during the $n^{th}-1$ beacon interval, respectively. A flow which is granted SMAA$^j_{i_{LiFi}}(n)$ again transmits the lost packets during the n^{th} frame. This does not include the dropped packets due to BS buffer overflow. At the end of each beacon frame, the active MDs report the SMAAs of all generated flows to the AP. This calculates the average SMAA of all admitted traffic flows in each class and broadcasts it with its corresponding TSPEC in the next frame to all MDs.

The value of SMAA indicates the Li-Fi and Wi-Fi medium access resource utilization [12]. A MD, before requesting Li-Fi or Wi-Fi medium access for a real-time flow, calculates its admission control parameters based on the requested QoS parameters subscribed in TSPEC. These include the maximum collision rate (η_i^{max}), R_i, and TXOP$_i$. The MD compares its tolerable η_i^{max} with the current channel collision rate, η_i^{curr}. If $\eta_i^{curr} > \eta_i^{max}$, the flow is rejected, as neither its delay nor throughput would be guaranteed [13]. The Li-Fi or Wi-Fi channel data rate of MD-i should satisfy the constraint (13) to support K flows.

$$R_i \geq \sum_{k=1}^{K} GBR_{ik}. \quad (13)$$

If the flow request is accepted by the MD, it is passed to the AP(s) from which receives a good signal strength. The APs coordinate its admission with the SDN controller, as illustrated in Fig. 1. The differentiated medium access-flow admission control (DMA-FAC) scheme decides based on the data rate when a flow requests admission in the Li-Fi access network and on the time access availability in Wi-Fi access network. The f_{K+1} is admitted in the L-Fi or the Wi-Fi based on the following admission constraints:

$$\gamma^{req}_{K+1} + SMAA^{K+1}_{LiFi} + \sum_{i=1}^{K} \gamma^{req}_i + SMAA^i_{Li} \leq \epsilon_L SDR_{Li} \quad (14)$$

$$\gamma^{req}_{K+1} \times SMAA^{K+1}_{WiFi} + \sum_{i=1}^{K} \gamma^{req}_i \times SMAA^i_{WiFi} \leq \epsilon_W SI_{WiFi}; \quad (15)$$

where γ^{req}_{K+1} is the requested data rate of f_{K+1}; SDR$_{Li}$ is taken to be the service data rate that meets the admitted traffic flows within the Li-Fi time frame. SDR$_{Li-Fi}$ is assigned as the maximum data rate of the frames transporting the admitted traffic flows during the SDN period of time, τ_S. Within the service interval (SI) of Wi-Fi the e2e delay requirements of all the admitted traffic flows are met. It is assigned as the minimum delay of all admitted traffic flows. The values of ϵ_L and ϵ_W define the target utilization level of the admitted real-time flows. They are dynamically adjusted by the SDN controller to support the minimum requirement of BE traffic flows. When the AP receives a request for a flow admission with no SMAA value, it decides based on its γ^{req}_{max} and η_i^{max} requirements to ensure the required QoS.

V. Performance evaluation

The network topology, depicted in Fig. 1, is considered in the simulation environment. It is composed of a Li-Fi AP and a Wi-Fi AP connected both to a SDN controller. This has software agents running in APs, which report resource availability and traffic flows statistics. Traffic flows generated from a MD are admitted in the network based on the developed DMA-FAC and MAC resource allocation scheme, subject to inherent communication and technology constraints. A simulation environment is developed in NS-3 and results are post-processed in MATLAB to evaluate the performance of the proposed scheme. It consists of triple-play traffic flows (video, voice, ethernet data) generation and a software module for integrating OFDMA-based Li-Fi and CSMA/CA-based IEEE 802.11e Wi-Fi medium access protocols. The main medium access parameters of Li-Fi and Wi-Fi APs are summarized in Table. I.

MDs generate CBR (voice), VBR (video) and BE traffic flows of various average data rates, 64, 1024 , 1500 kbps respectively. The packet size of voice, video, and BE traffic flows is 80,500,1500 bytes, respectively. Voice, video and data traffic flows are generated simultaneously during the simulation running time of 100s. The proposed scheme aims to meet the flows' QoS performance targets described in Table. II. While the BE traffic flows do not have QoS targets, the proposed scheme exploits the maximum aggregated capacity of Li-Fi and Wi-Fi APs to offer acceptable data rates to BE flows. The different access categories are defined in Table I.

TABLE I
Li-Fi and Wi-Fi MAC parameters and Token Bucket Parameters.

	CBR (Voice)	VBR (Video)	BE
AIFS	25 μ s	25 μ s	34 μs
CW$_{min}$	15	31	63
b$_{DTLB}$(bits)	640	4000	-
r$_{DTLB}$(kbps)	64	1024	-
P$_{DTLB}$(kbps)	80	1300	-
	Li-Fi	Wi-Fi	-
Phy rate	20 Mbps	36 Mbps	-
Minimum BW	6 Mbps	6 Mbps	-
Slot time	70 n s	9 μ s	-
SI	50 ms	120 ms	-

Three scenarios are conducted to evaluate the performance of the proposed scheme: i) running the L-Fi/Wi-Fi network without flow admission control (W-FAC). The traffic flows

TABLE II
QOS TARGETS OF THE DIFFERENT APPLICATION FLOWS

Flow type unit	Data rate kbps	Delay ms	Packet Dropping %	Jitter ms
CBR voice	64	20	3%	1
VBR video	1024	40	1%	-

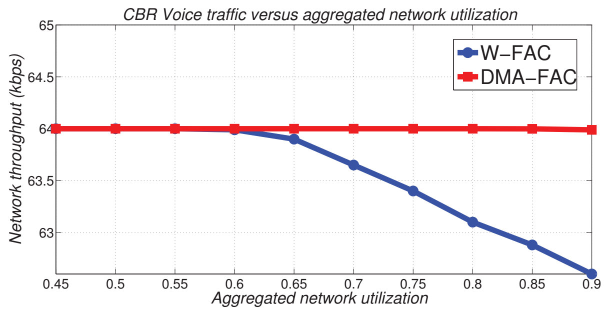

Fig. 3. CBR Voice throughput versus aggregated network utilization.

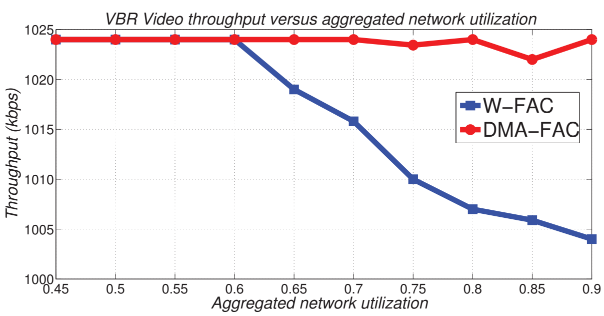

Fig. 4. VBR video throughput versus aggregated network utilization.

are established based on the default MAC protocol parameters of Wi-Fi and Li-Fi APs; ii) running the Li-Fi/Wi-Fi network with DMA-FAC scheme. The traffic flows are offered differentiated medium access based on its QoS requirements; and iii) running the Li-Fi/Wi-Fi access network in a hybrid or aggregated mode. The performance metrics which reported in these simulation scenarios are: per-flow class throughput, per-flow class mean delay, overall aggregated network capacity efficiency in terms of the number of admitted traffic flows.

The obtained results show that without controlling traffic flows admission, the QoS targets of real-time flows cannot be satisfied despite resource availability in the Li-Fi/Wi-Fi network. The throughput of CBR flows could be guaranteed until a traffic load corresponding to 0.6 of network utilization level, where a decrease in throughput is observed, as shown in Fig. 3. The proposed DMA-MAC scheme monitors the network through SDN and thus could efficiently match traffic flows with available resources in the network. This explains the trends of maintaining the throughput of CBR voice and VBR video flows, as shown in Figs. 3 and 4. The throughput of CBR and VBR flows could be maintained during the simulation time independent of network utilization level. However, the bursty nature of VBR flows may explain the small decrease

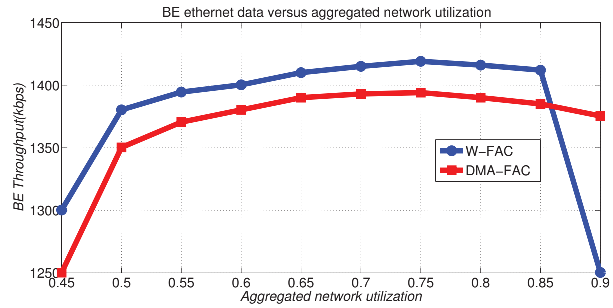

Fig. 5. BE ethernet data throughput versus aggregated network utilization.

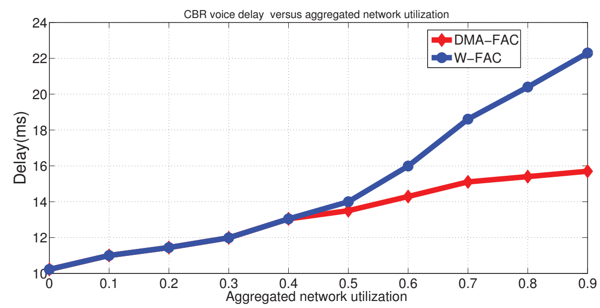

Fig. 6. CBR voice delay versus aggregated network utilization.

in its throughput at the end of the simulation time. It also explains the decrease in the throughput of VBR flows when the network is running without FAC scheme. In this case, more resources are made available for BE ethernet data flows, which explain their throughput increase shown in Fig. 5. When real-time traffic load becomes higher, BE could not access more resources. This explains, in turn, the sharp decrease of BE throughput shown in Fig. 5.

Queuing, propagation and transmission times are the main sources for delaying traffic packets. The queuing delay is measured from when the packet is queued in the MD until it accesses the wireless medium. The transmission delay is measured as the time difference between the first bit arrived and the last bit transmitted of a packet. The DMA-FAC calculates the admission control parameters based on the QoS targets of flow and not based on the requirements of its service access class. This explains why the proposed DMA-FAC scheme could maintain the delay targets of CBR and VBR flows independent of the network resource utilization, as shown in Fig. 6 and Fig. 7. Voice and video traffic flows have an increase in delay after a network utilization level, when the network is running without FAC, as shown in Fig. 6 and Fig. 7. Because of the bursty nature of VBR flows, some packets may not be transmitted in the allocated TXOP and SMAA, which results in increasing its flow queuing and transmission delays. Without FAC the delay target of video flows cannot be upper bounded, which becomes clear when the network utilization reaches a high level, as shown in Fig. 7. The DMA-FAC allocates different SMAAs for different flows based on per-flow packets decrease, loss or collision rate. This kept the

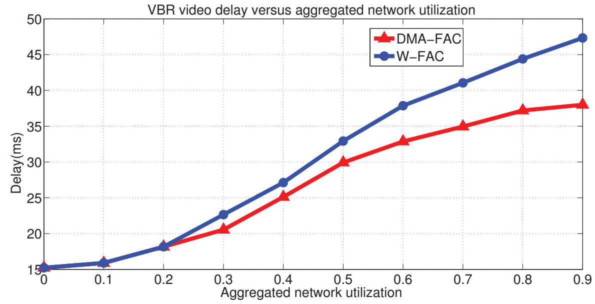

Fig. 7. VBR video delay versus aggregated network utilization.

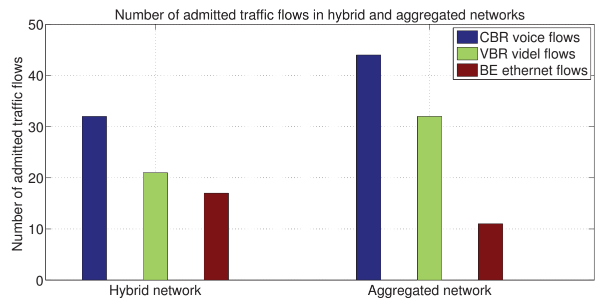

Fig. 8. Number of admitted flows in hybrid and aggregated Li-Fi/Wi-Fi networks.

delay of the admitted voice and video flows below its targets despite the increase in network utilization, as shown in Fig. 6 and Fig. 7

Each MD generates a number of 50 flows of VBR, CBR and BE, separately, and a total of 150 flows of variable rates requested admission in a network running in the hybrid and aggregated network modes. In the hybrid mode, the SDN controller assigns requests separately to each AP, whereas in the aggregated network mode it applies traffic splitting rules among the APs based on flows data rates and other cognitive service policies. As a result, the number of admitted real-time voice and video flows is higher in the aggregated network mode, as shown in Fig. 8. The number of BE data flows could have more resource access in the hybrid mode than the aggregated network mode. This explains the decrease in the number of BE flows in the aggregated network mode compared with that in the hybrid network mode, as shown in Fig. 8.

VI. Conclusion

This paper contributes to the research efforts led by standardization bodies that define approaches to increase the data rates of heterogenous wireless networks through leveraging their capacity diversity to support more real-time flows in an efficient resource-manner. In this paper, a novel SDN scheme is introduced which leverages the diversity of the QoS targets of MD applications and the capacity diversity of Li-Fi and Wi-Fi access networks to support more real-time flows anytime, anywhere. The scheme comprises entities running in the MD applications and MAC layers of both OFDMA-based Li-Fi and CSMA/CA-based IEEE 802.11e Wi-Fi which use cross-layer parameters to aggregate the capacity of both access networks and support differentiated medium access per-flow QoS requirements. The obtained results show that the aggregated Li-Fi/Wi-Fi network should have a flow admission control to accept more real-time flows and maintain its QoS targets within acceptable bounds while offering acceptable data rates to BE traffic flows. A multi-service Li-Fi frame structure supported with a novel MAC protocol P-FSRP is also introduced to support the capacity aggregation of Li-Fi and IEEE 802.11e Wi-Fi network. The SDN controller could dynamically control the parameters of both mediums' parameters through their respective APs to support bandwidth aggregation and admit more real-time flows.

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